Brazing Dissimilar Metals with a Novel Composite Foil

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June 7, 2016

JOHNS HOPKINS
WHITING SCHOOL of ENGINEERING

Project ID
LM098

Overview

Timeline

- Start date: September 1, 2013
- End date: August 30, 2017
- Percent complete: 50%

Barrier

- Joining and assembly. High-volume, high-yield joining technologies for lightweight and dissimilar materials need further improvement.

Budget

- Project budget: $595,520
  - Budget Period 2: $149,167

- JHU Contribution from fellowships: $45,300

Project Partners

- Dr. Karsten Woll (former postdoc) – now with Karlsruhe Institute of Technology, Karlsruhe, Germany

Relevance – Project Objectives

Overall Objective: Develop and characterize novel reactive foils based on reduction-oxidation (Redox) reactions for use in bonding dissimilar materials

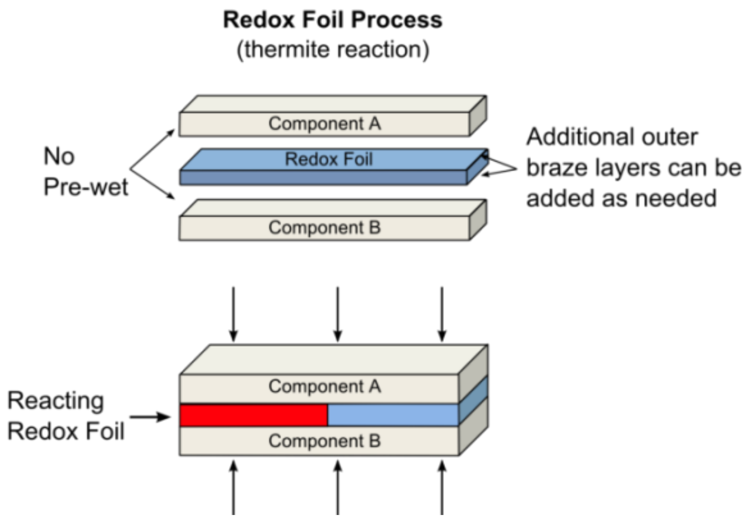
Achievements for FY2015:

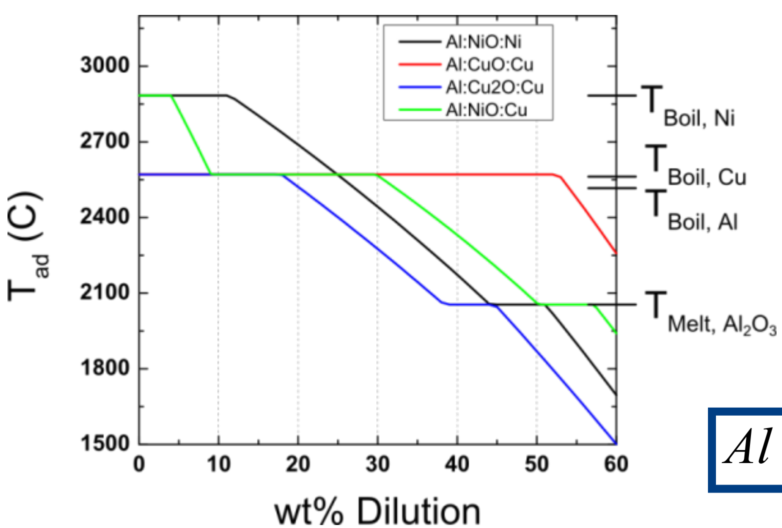
- Determined best chemistry Redox Foil was the Al:Cu_2O system
- Increased quantity of braze in Al:Cu_2O foils from 65vol% to 74vol% by utilizing ball-milled thermite powders
- Enhanced propagation velocities and lowered risk of quenching by incorporating ball-milled thermite powders
- Achieved dissimilar bond strengths as high as 10 MPa

Milestones

Task	2014				2015				2016				2017				Milestones	Status
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4		
1. Optimize Foil Properties																		
1.1 Optimize chemistry							M1										Dissimilar Bonds with strength 10MPa	Complete
1.2 Optimize microstructure							M2										Microstructures with no gas production and quenching	Complete
1.3 Optimize mechanical fab									M3								Optimized methods for mechanically fabricating Redox Foils	On Track
2. Optimize Bonding Parameters																		
2.1 Applied pressure											M4						Optimize applied pressure	On Track
2.2 Foil thicknesses											M5						Optimize foil thickness	On Track
2.3 Surface preparation												M6					Optimize surface preparation. Strength greater than 20 MPa.	On Track
3. Characterize Bond Properties – Microstructure																		
3.1 Bond strengths																M7	Statistical bond strength data	On Track
3.2 Failure modes																M7	Determine failure modes of bonds	On Track
3.3 Corrosion behavior															M8		Determine galvanic corrosion behavior of optimized bonds	On Track
3.4 Bond/component microstructure																M9	Analyze microstructure at bond interface	On Track
3.5 Component degradation																M9	Analyze degradation of bonds	On Track

Approach – Exothermic Brazing





- Redox Foils: nearly fully dense diluted thermites
  - Produce braze and heat
    - Al:NiO:Ni
    - Al:NiO:Cu
    - Al:Cu_2O:Cu
    - Al:CuO:Cu

- Dilute with excess metal to decrease amount of gas produced
  - Want T_{ad} below boiling points

$$Al + MO + \text{dilution} \rightarrow Al_2O_3 + (M + \text{dilution}) + \text{heat}$$

Approach – Fabrication and Utilization

- Redox Foils fabricated by consolidating, swaging, and rolling micron sized powders

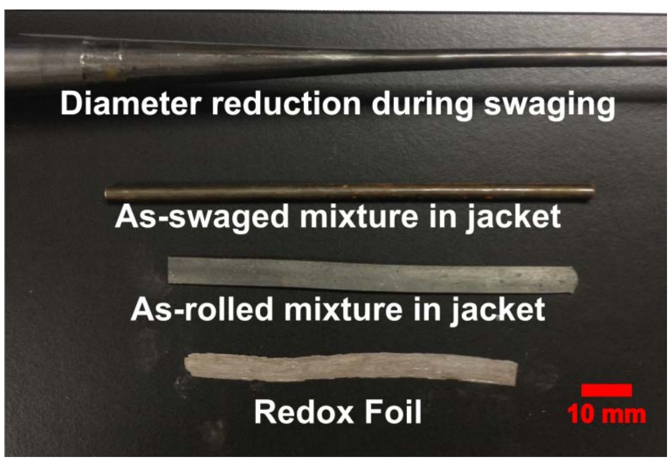
Fuel

Oxide

Al:NiO:20%Ni

Diluent

Redox Foil Fabrication

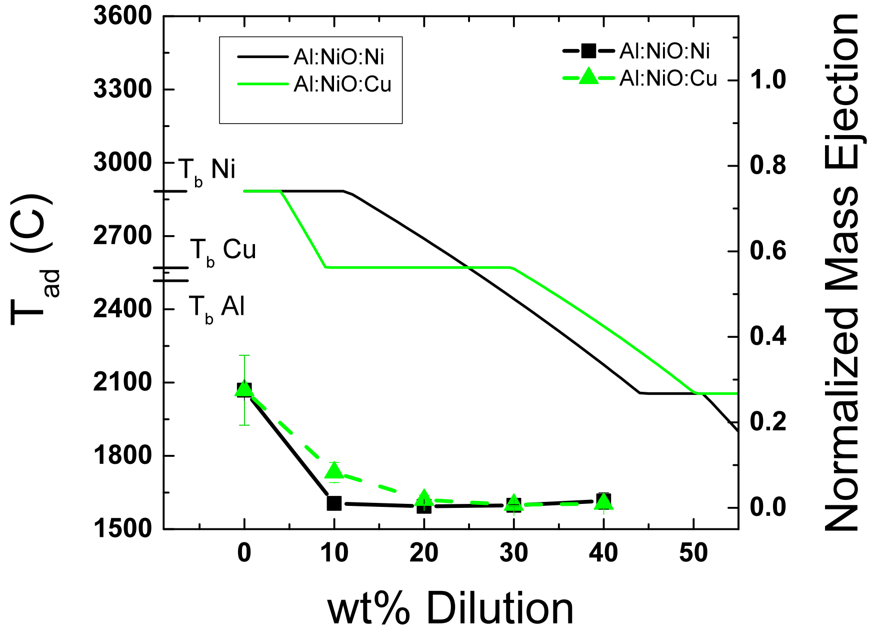


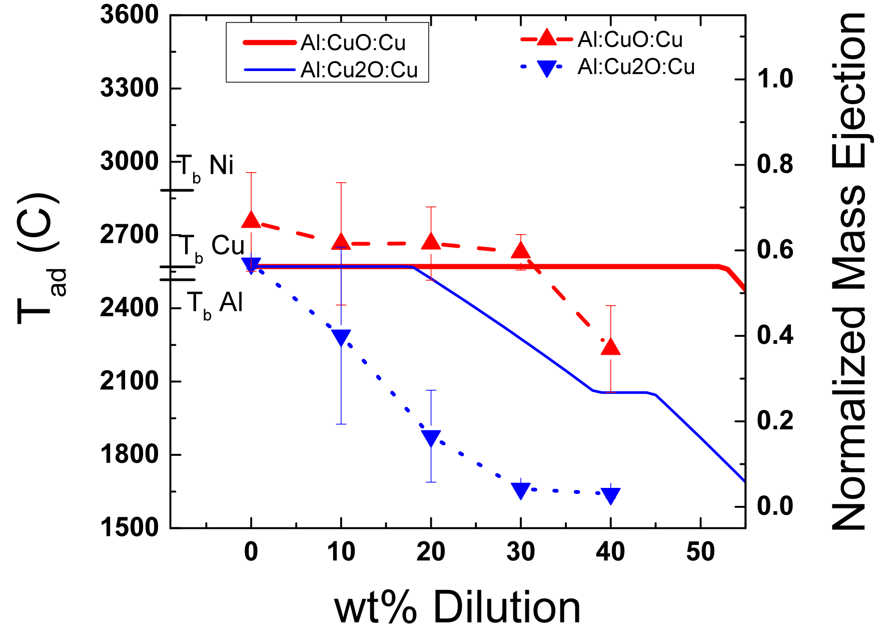
Real Time

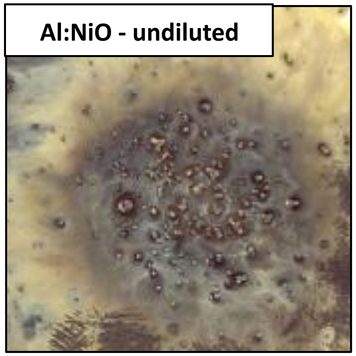
8000 Frames per second

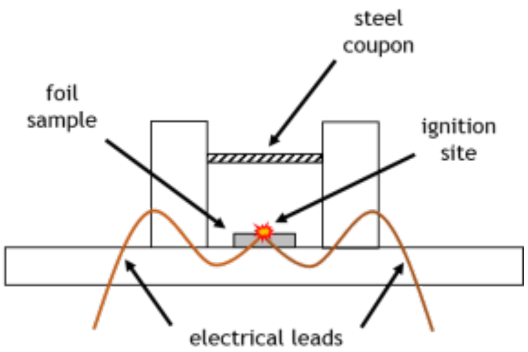
Al:NiO:10%Ni

Previous Work – Effect of Dilution

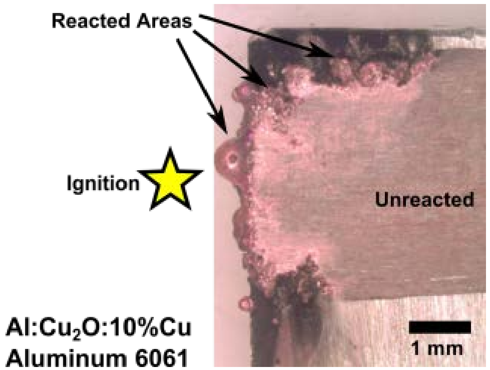






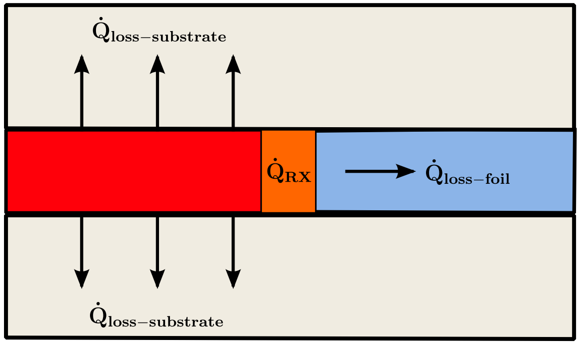


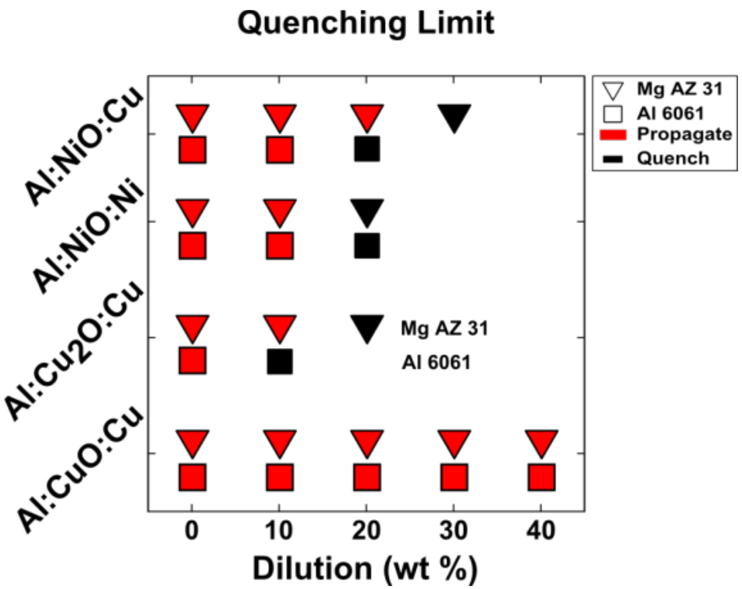
Previous Work – Quenching

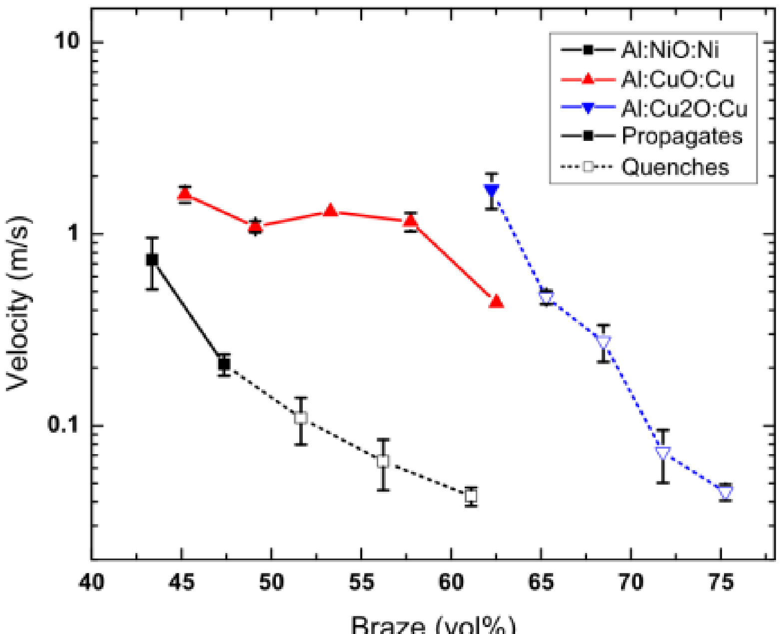


Necessary condition for propagation in bond:

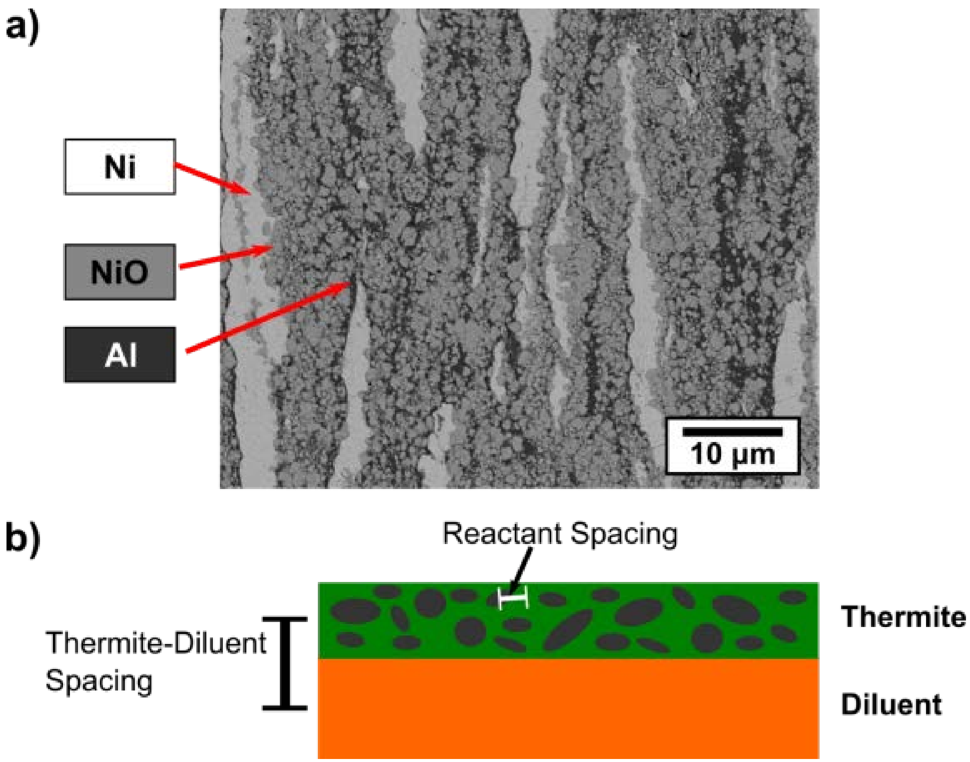
$$\dot{Q}_{RX} > \dot{Q}_{loss}$$







Accomplishments – Microstructure

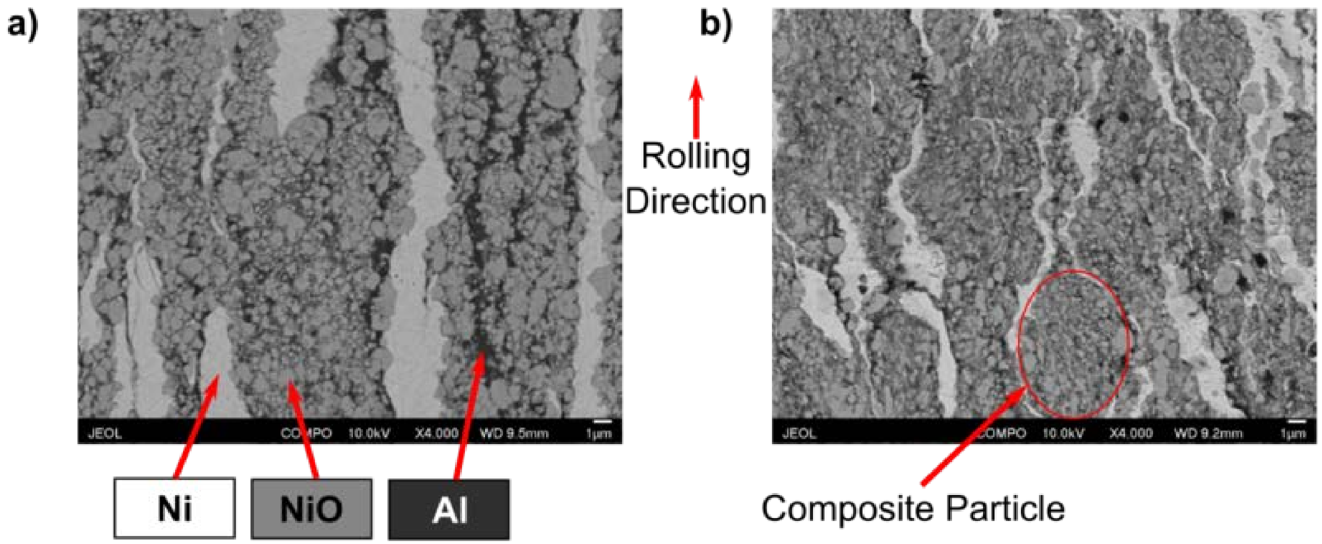


- Spacing between Al and metal oxide (NiO/CuO/Cu_2O) determines reactivity.
- Reactant spacing is on the order of 1-3 microns
- Previous Barrier – reduce reactant spacing to enable propagation at higher dilutions

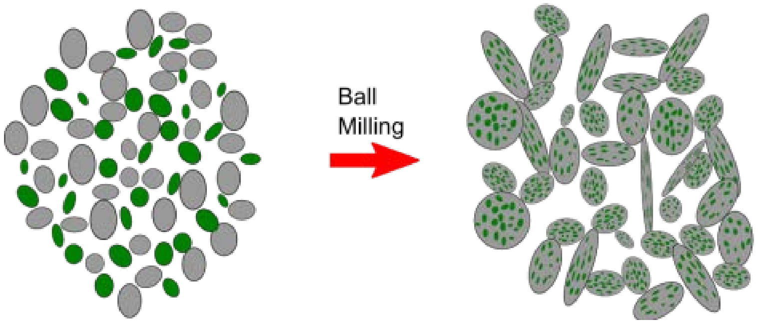
Ball Milling

Conventional Redox Foil

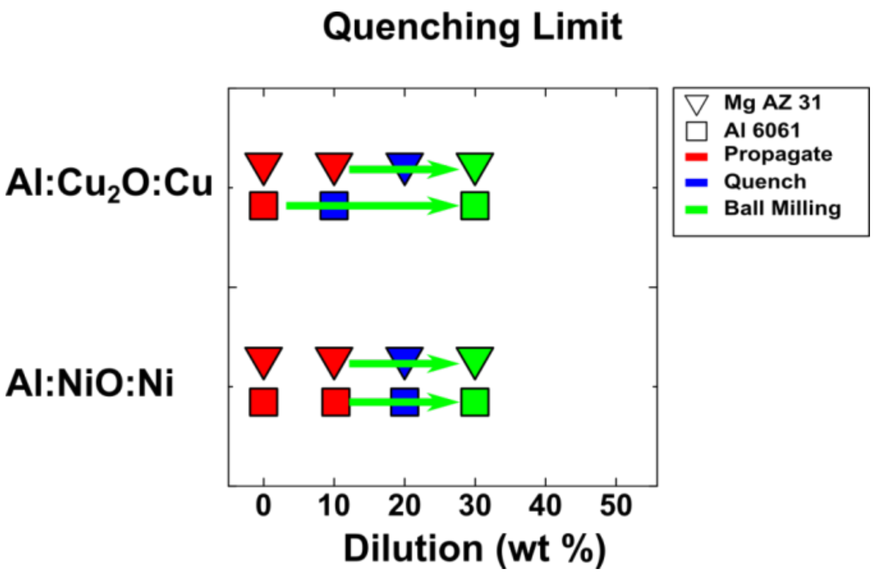
Ball-Milled Redox Foil

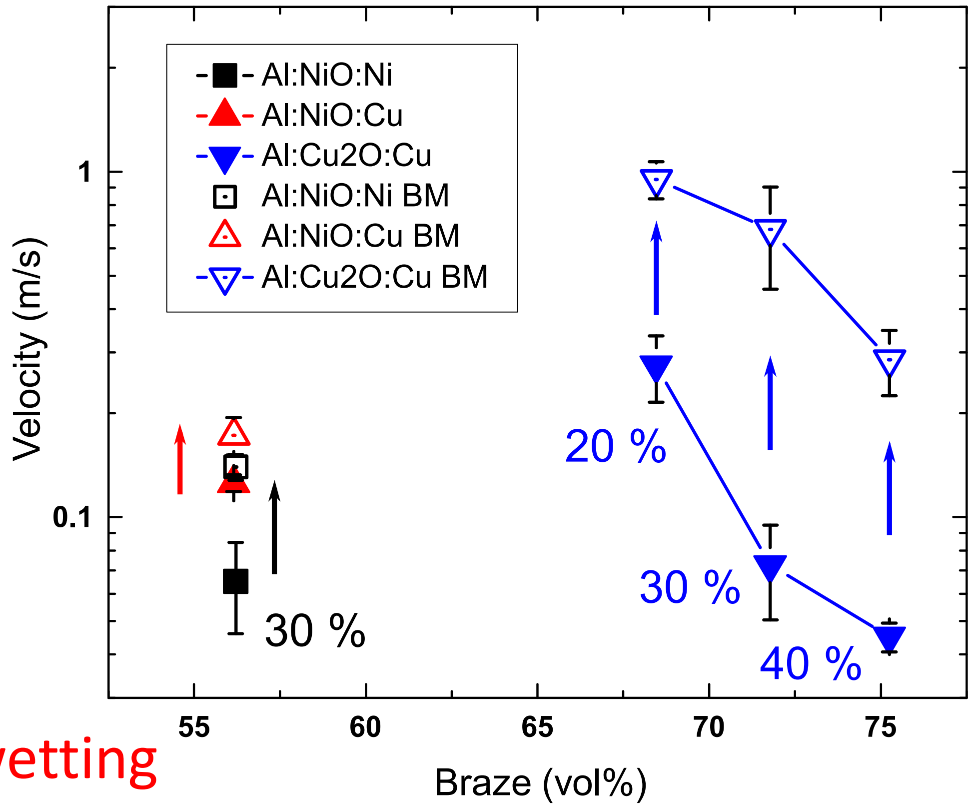


- Spacing between Al and metal oxide NiO/CuO/Cu_2O determines reactivity and is reduced in the ball-milled Redox Foil.
- Ball-milled reactant spacing is sub micron.



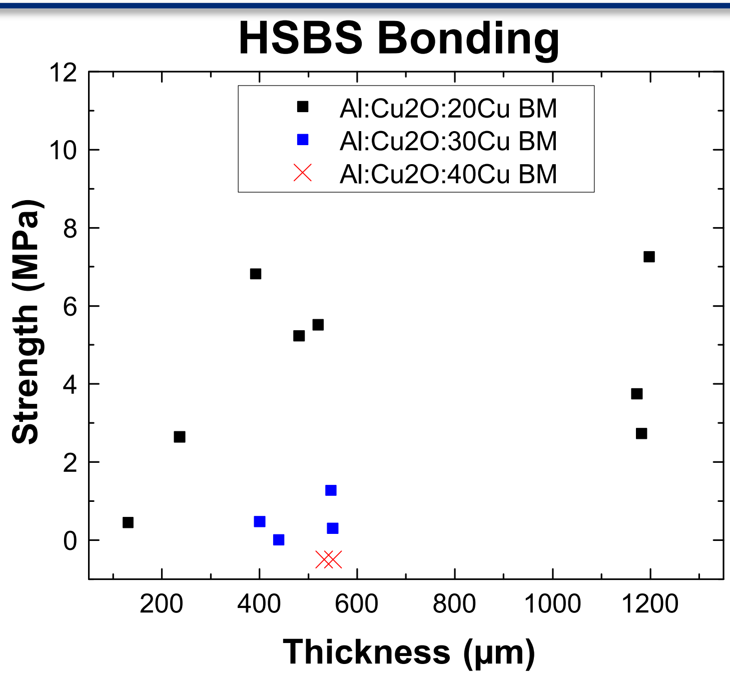
Velocity Quenching Enhancement

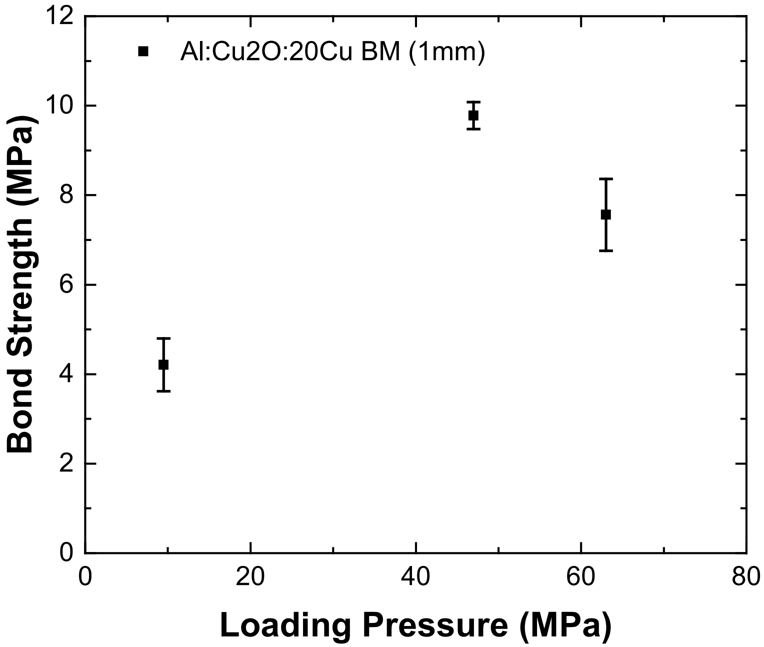




- Al:NiO:Ni
- Al:NiO:Cu – less braze, poor wetting
- Al:CuO:Cu – too much gas
- **$Al:Cu_2O:Cu$ – best candidate**

Bond Strength

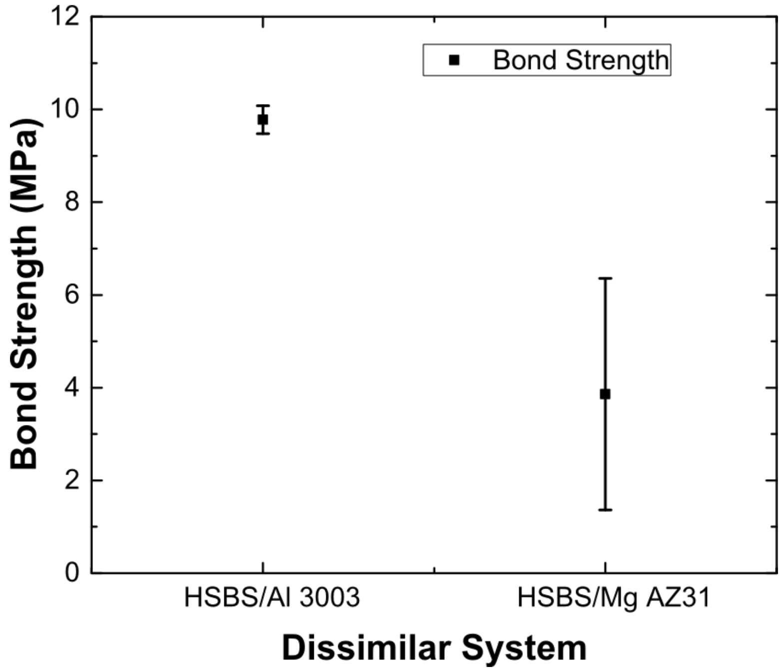




- Bonding High Strength Boron Steel (HSBS) to itself
- For Cu dilution, 20wt% is best
    - Cu molten too briefly at higher dilutions
    - Braze with lower T_m may help
- Strength depends on foil thickness

- Bonding HSBS to Al/3003
- Strength depends on loading parameters

HSBS/Al vs HSBS/Mg



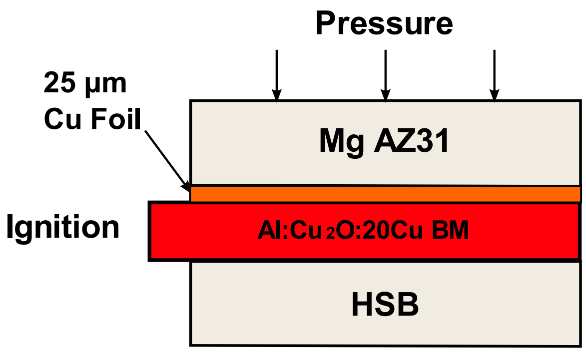
- HSBS/Mg weaker than HSBS/Al due to excessive melting of Mg surface

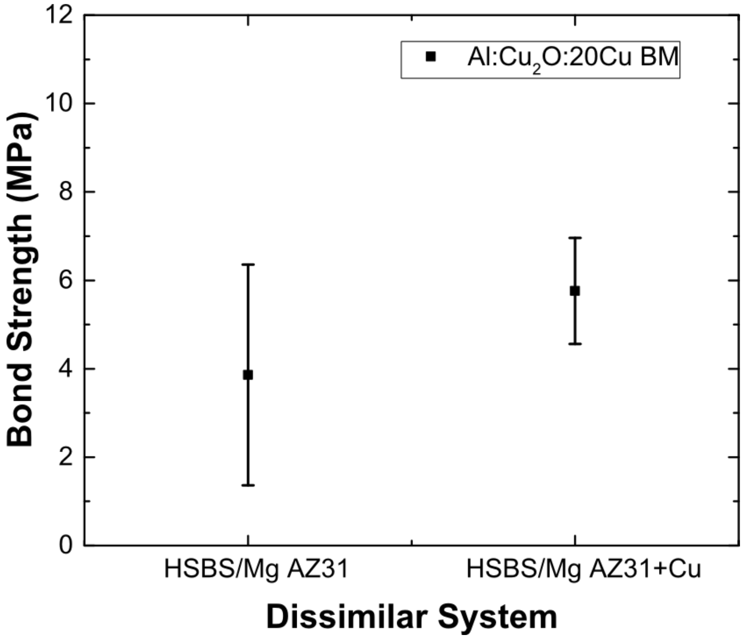
Large magnesium melting

Top-Mg AZ31

Bottom-HSBS

Adding Excess Copper





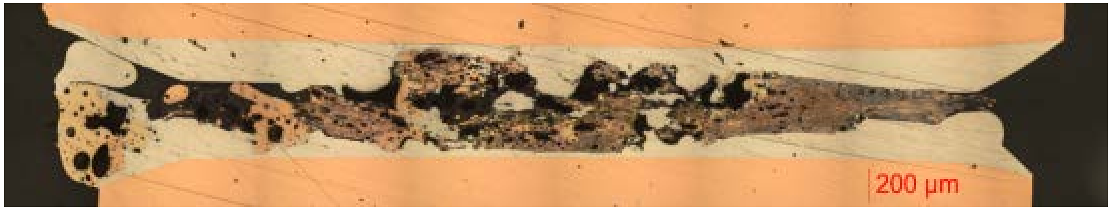
Excess Cu

- Adding Cu foil minimizes excessive melting of Mg
  - Increases bond strength

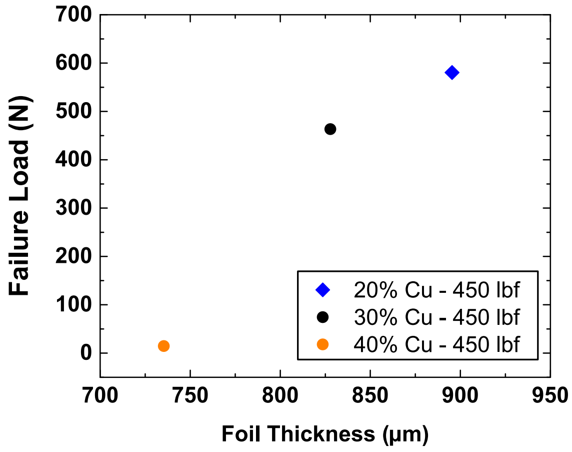
Bond Cross Sections – Porosity

20%Cu

30%Cu



40%Cu

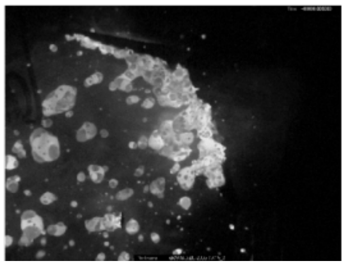


- Tin-Silver coated Cu samples joined with Al:Cu_2O:Cu BM Redox Foils to assess ejection
  - As dilution increases, porosity decreases
  - Substantial ejection still visible for 20wt% even though $T_{ad}<T_b$

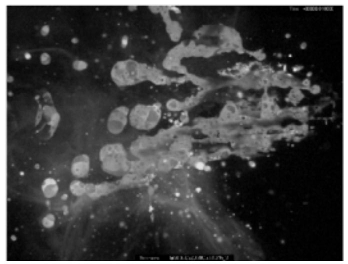
Cause of Porosity

- BM foils still generate gas, despite high dilution

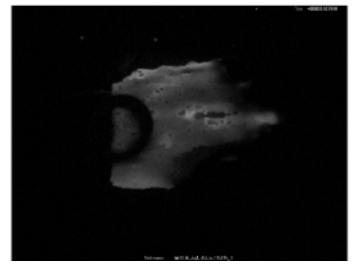
$Al:Cu_2O:20Cu$ BM

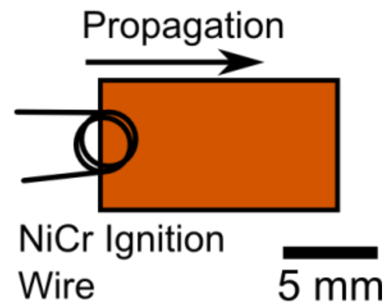


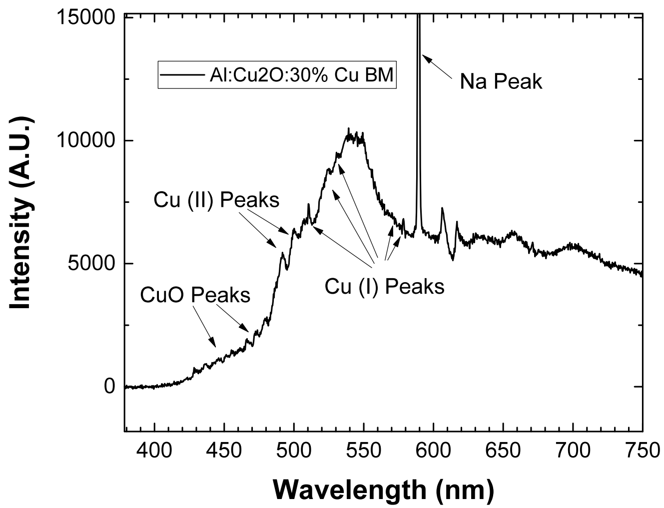
$Al:Cu_2O:30Cu$ BM

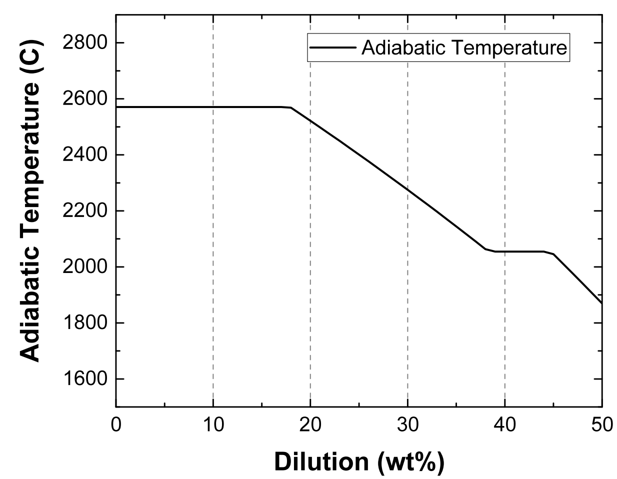


$Al:Cu_2O:40Cu$ BM

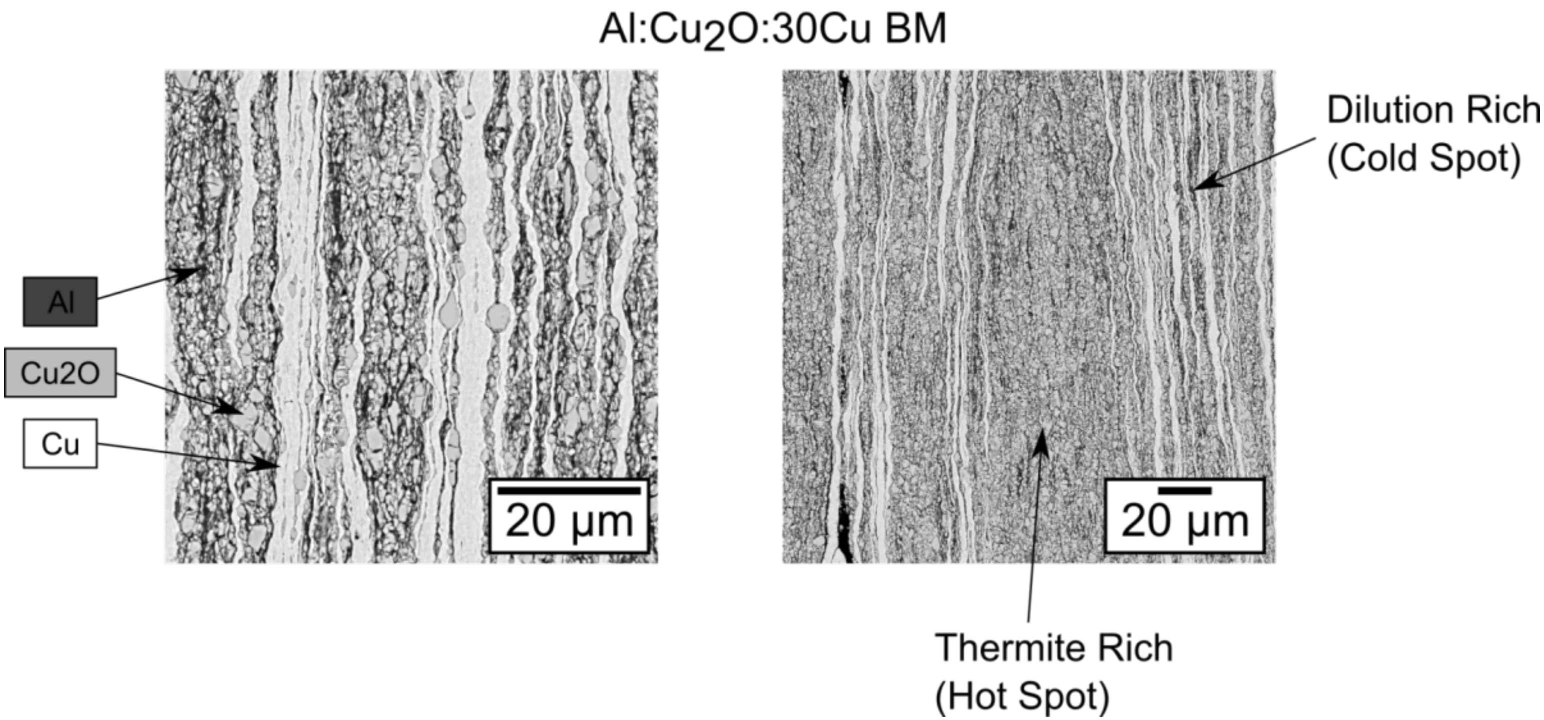








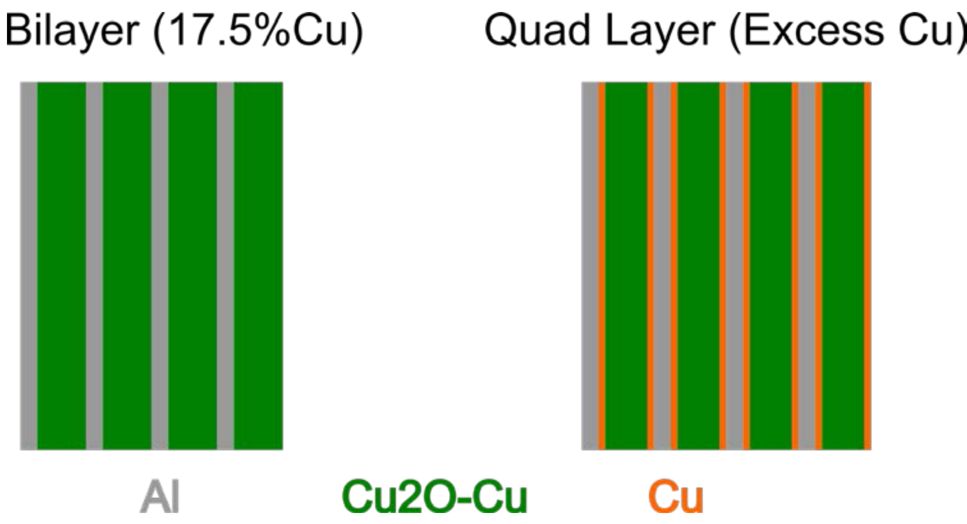
Explanation – Hot Spots

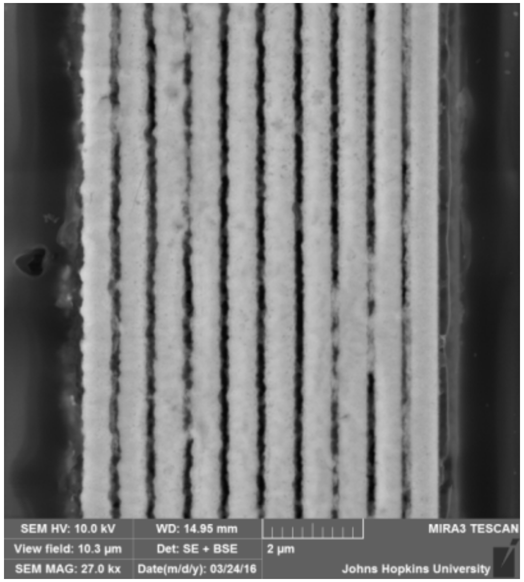


- High local concentration of thermite produces heat faster than can be dissipated into the Cu diluent
  - Locally, $T > T_{ad}$ and $T > T_{boiling}$
  - Produces gas which yields mass ejection and pores

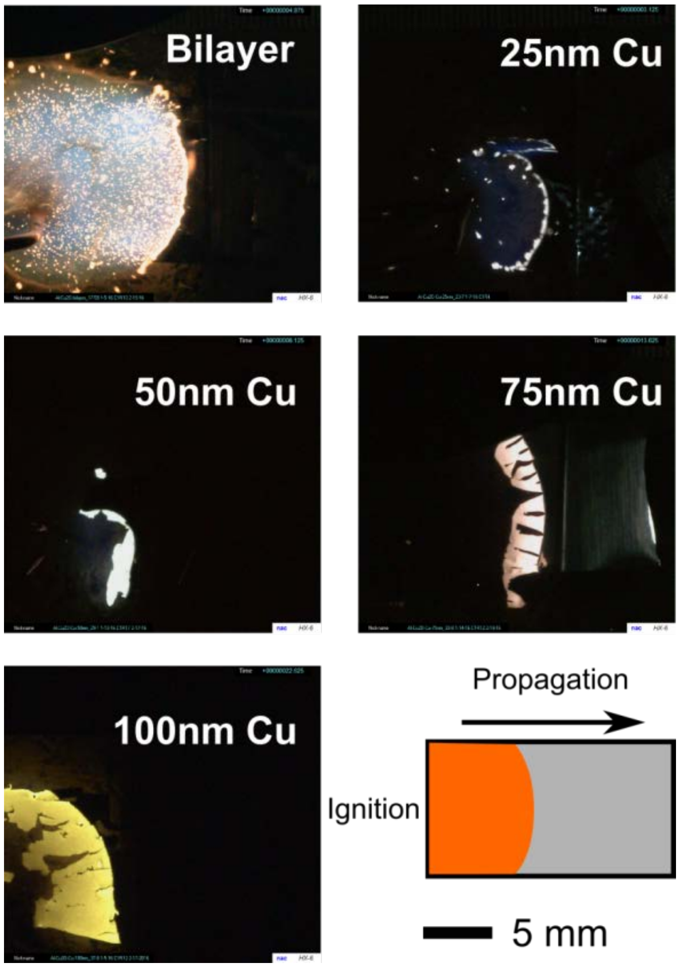
PVD – Model System

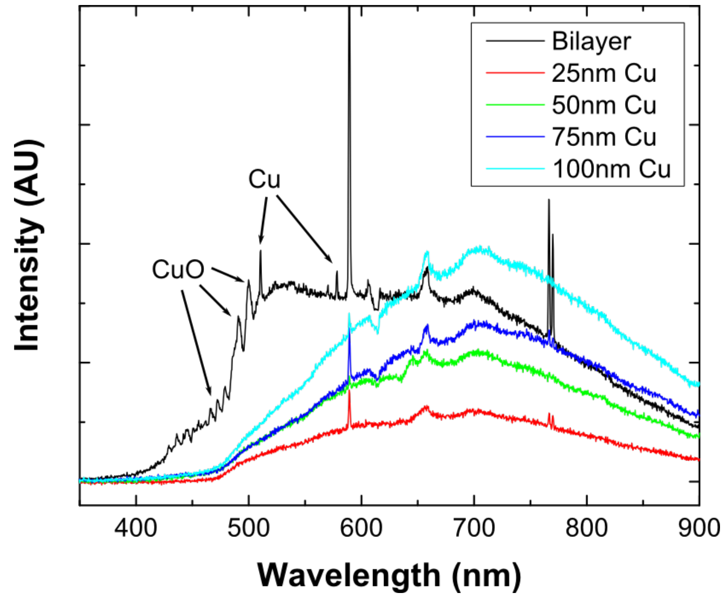
- Produce vapor deposited thermite foils
  - Well defined spacing and dilution
- Dilution added with Cu layers into the multilayered structure
- Foils 10 µm thick
- **If PVD is gasless, then mechanical system is viable**

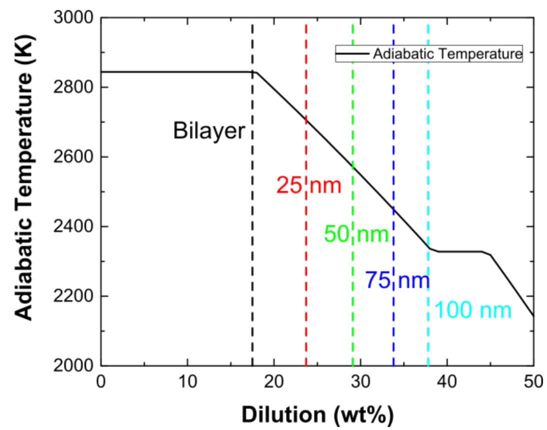




PVD – Gas Suppression

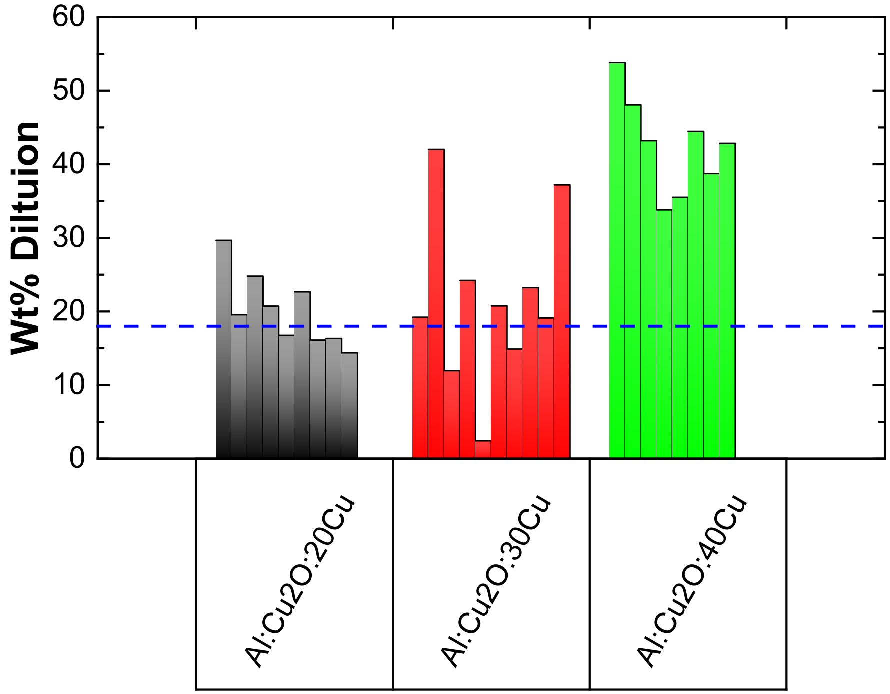


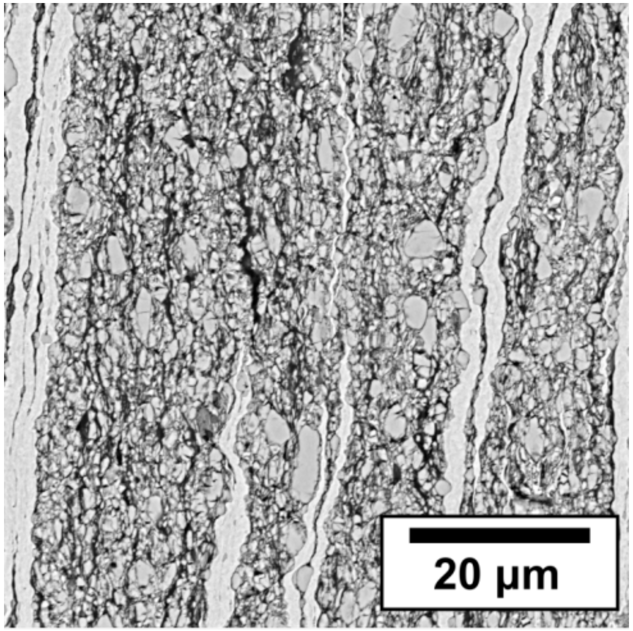




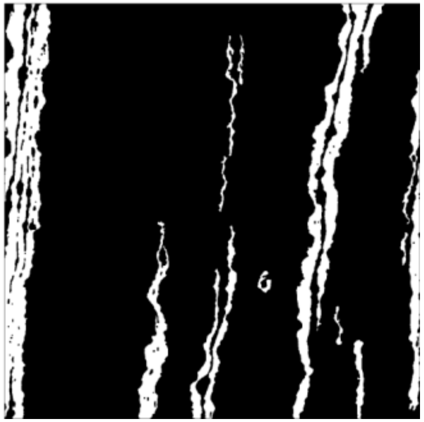
Vapor only detected in bilayer - no gas production with dilution – extend to BM processing

Local Dilution



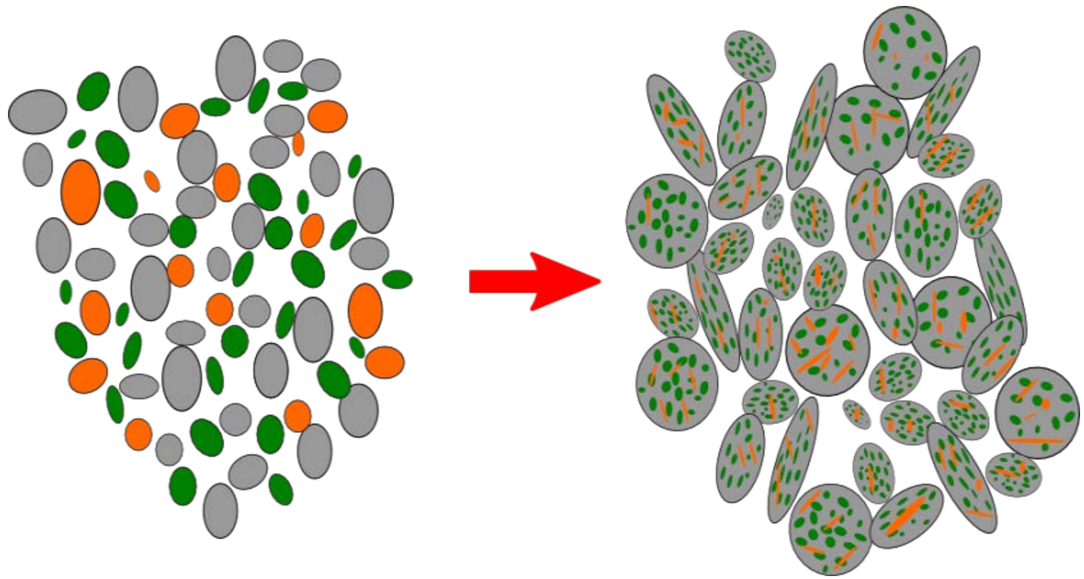


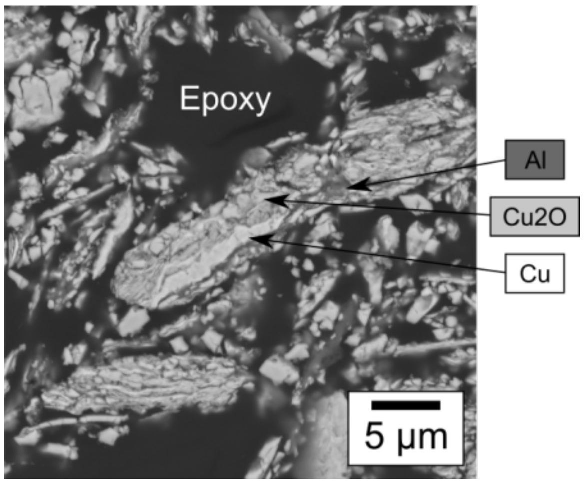
Al:Cu_2O:30Cu BM Threshold Image



- Image analysis determines local dilution
  - Locally, 20wt% and 30wt% foils fall below critical dilution for gas generation
  - Must improve uniformity of diluent

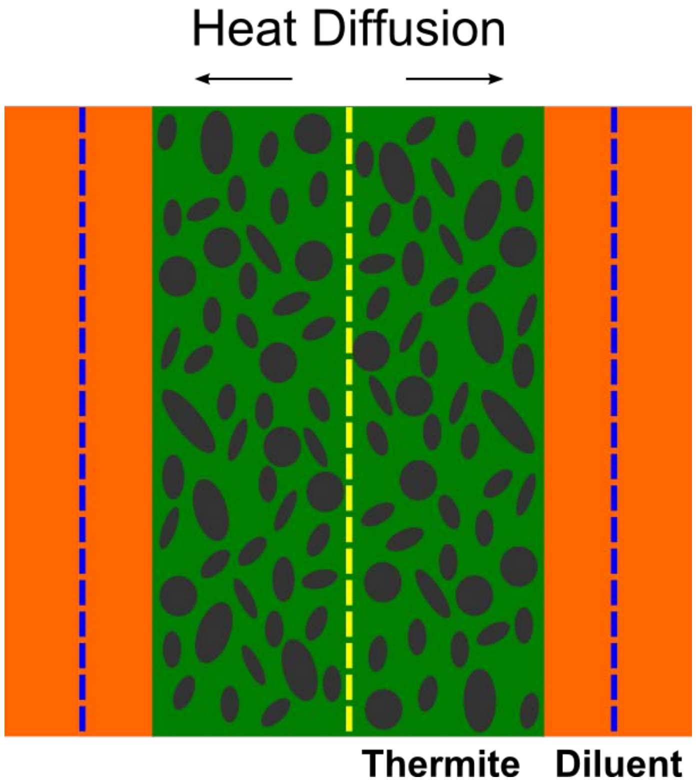
In Progress – Mill with Diluent





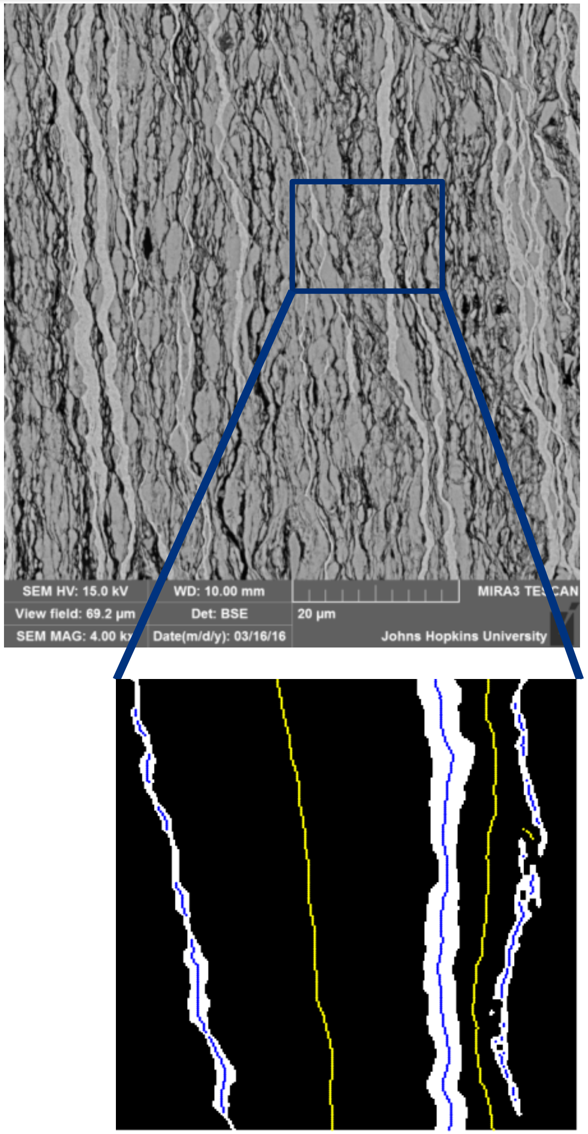
- Milling with diluent will increase homogeneity of Redox Foil microstructure.
  - Reduce heat diffusion distances

In Progress – Modeling Heat Diffusion

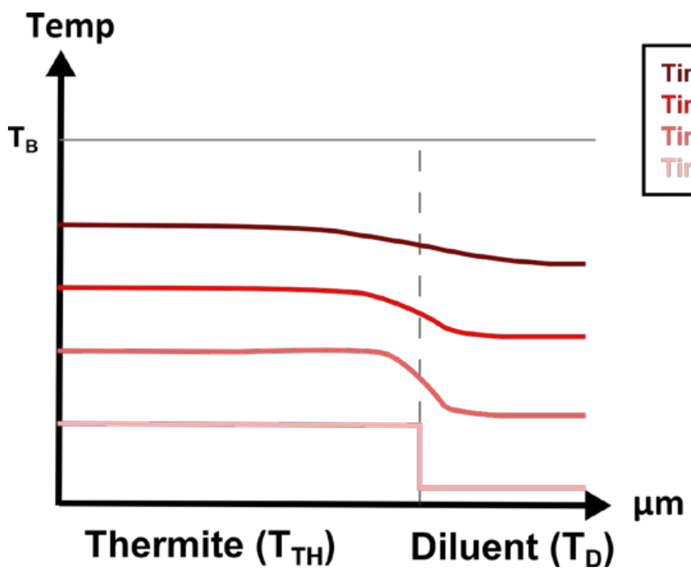


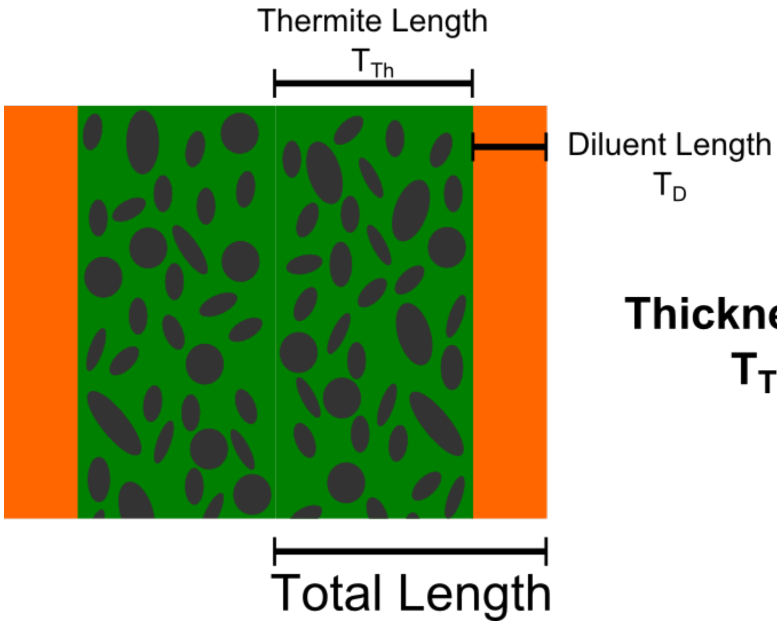
$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} + \dot{Q}_{src}$$

$$\alpha = \frac{k}{C_p \rho}$$



In Progress – Modeling





Thickness Ratio
T_{Th}/T_D

- Assess local temperatures in reaction zones (does local T_{rx} rise above T_b?)
  - Vary thermite:diluent ratio
  - Vary distances

wt% Dilution	Thermite:Dilutent Thickness Ratio	Total Length		
10	15.27	1 µm	10 µm	50 µm
20	6.79			
30	3.96			
40	2.55			

Response to Previous Year Comments

- *The reviewer also suggested a slide that shows a structured research approach, such as a series of designed experiments for identifying the particular chemistries and process parameters…The reviewer suggested that a fishbone or other diagram identifying the variables and their levels and how the tasks are addressing determining their optimal level would be helpful.*
  - We have identified best chemistry as Al:Cu_2O thus minimizing the number of variables.
  - Need to determine best dilutions, reactant spacing, and diluent spacing to produce foils that do not generate gas.

- *The reviewer suggested that a slide on the mathematical modeling and simulation would be good to improve the proposed research plan and suggested an improvement to the future work would also be a slide on the structured method by which the future work goals will be accomplished. The reviewer stated it may be an educational improvement to clarify what is known and is the starting point and what has been learned through this project. The reviewer also questioned if there were any statistical significance tests that have been performed.*
  - A slide on our proposed modeling plans has been included.
  - No extensive statistical tests have been performed yet. Those tests will begin in the last year of the program, once ideal foils and bonding conditions have been determined.

Collaborations

- **Severstal** – Material supplier

  Supplied aluminum-coated boron steel and hot-stamped boron steel for testing

- **Dr. Karsten Woll** – Former postdoc

  Now at Karlsruhe Institute of Technology

Remaining Challenges and Barriers

Challenge: Mass ejection & porosity in bonds

Solution: Improve mechanical fabrication and distribution of powders to improve homogeneity of diluent and reduce hot spots

Challenge: Low melting/boiling temperature substrates (Mg) substantially melt/evaporate

Solution: Clad excess metal layers to decrease excessive melting

Challenge: Molten braze from Redox reaction wets poorly

Solution: Alloy best braze(s) with reactive elements

Challenge: Best braze(s) may lead to corrosion

Solution: Alloy braze systems to minimize corrosion

Future Work

- Ball mill Al, Cu2O, and diluent simultaneously to decrease local hot spots and produce optimized microstructure.
- Model heat dissipation into diluent layers.
- Alter the dilution chemistry to tailor the braze product of the reaction for specific bonding substrates.
- Continue optimizing bonding parameters for given Redox Foil/base metal couples, including optimization of surface preparation, bonding pressure, and foil thickness.
- Create statistically signification datasets for shear strengths of bonds and determine the modes of failure in the joint.
- Analyze the braze and base metal interface for any changes in mechanical properties of base metal due to heating from the reaction of the Redox Foil.

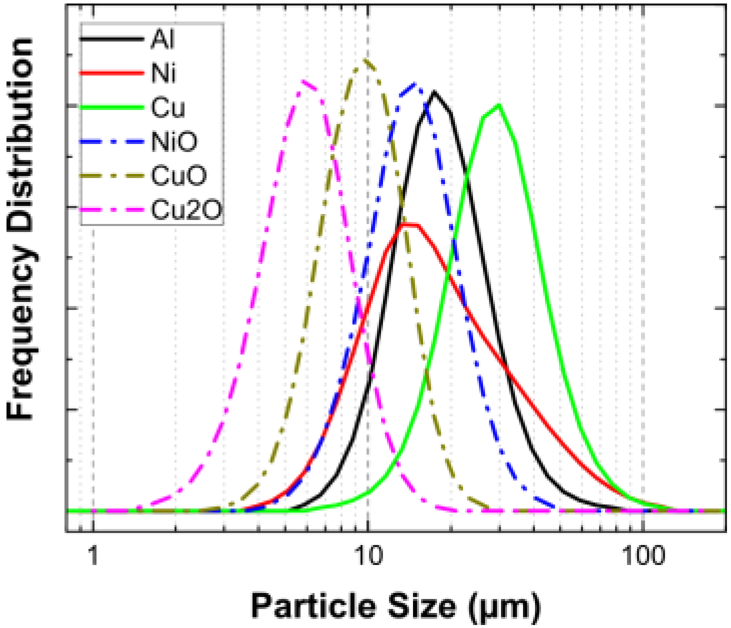
Summary

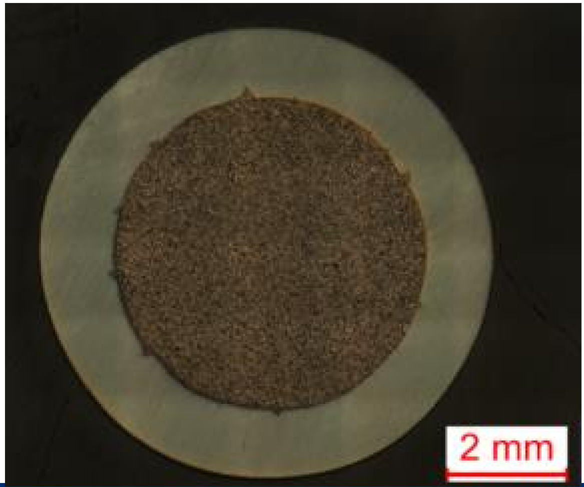
- Volume of braze was increased by incorporating ball-milled thermite powders.
- Optimum chemistry identified (Al:Cu_2O).
- PVD foils demonstrate ability to avoid gas production given controlled microstructure.
- Further refinement of milling conditions required to reduce hot spots and gas production

Technical Back-Up Slides

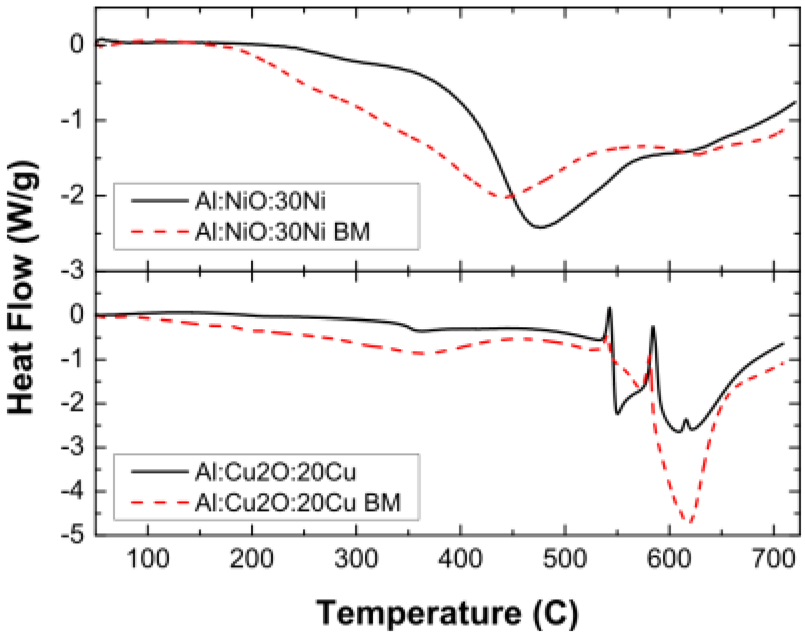
Mechanical Fabrication of Redox Foils

- Pack powders in tube
  - $Al:Cu_2O:Cu$
  - Al:CuO:Cu
  - Al:NiO:Ni
  - Al:NiO:Cu
- Process
  - Swage: radial reduction 0.59” to 0.22” or 0.125”
  - Roll to desired thickness
  - Remove steel jacket



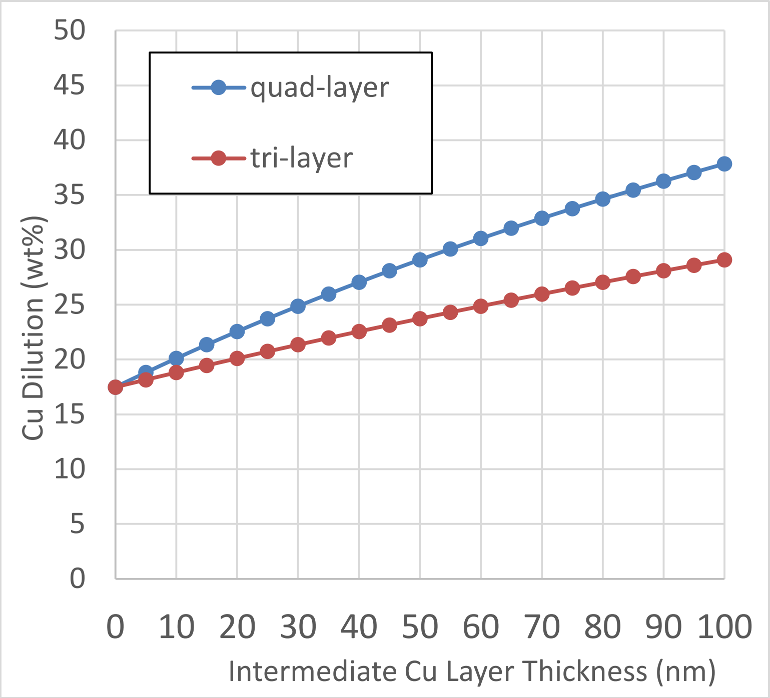


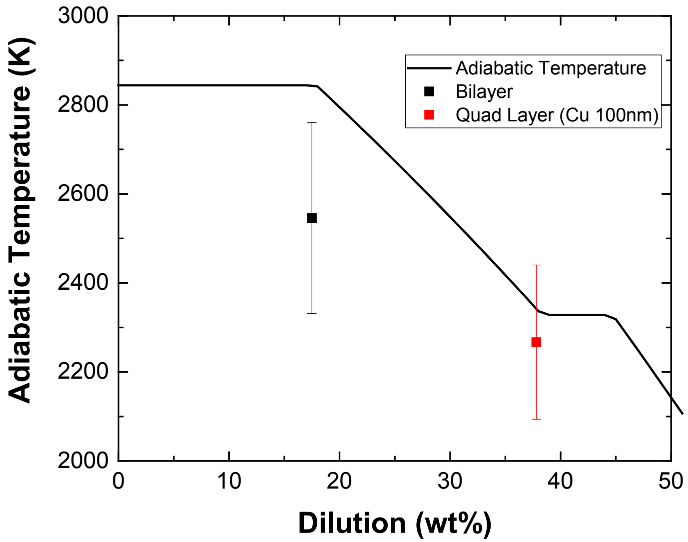
DSC Curve Shifts

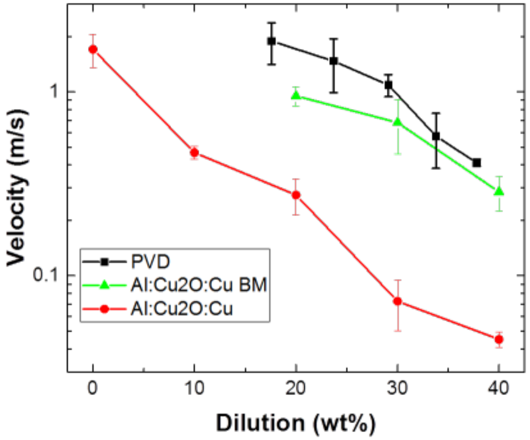


- Redox Foils with ball-milled powder have broader peaks with earlier onset and peak temperatures, indicative of finer reactant spacing

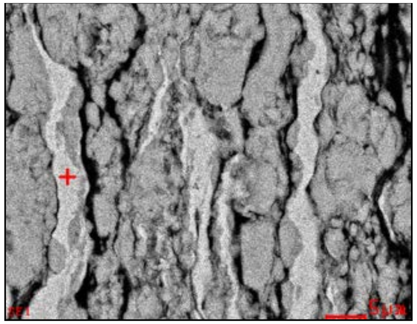
PVD – Velocity and Temperature



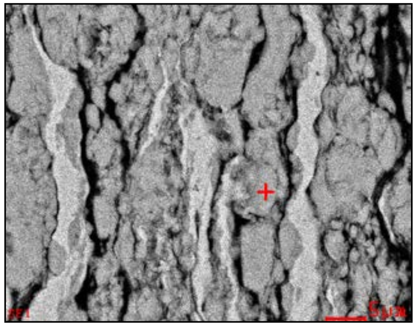




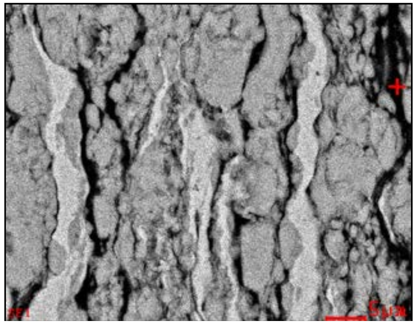
Composition Confirmation



Element	Wt%	At%
OK	01.30	04.86
CuL	96.98	91.32
AlK	01.72	03.82
Matrix	Correction	ZAF



Element	Wt%	At%
OK	09.91	30.05
CuL	88.97	67.94
AlK	01.12	02.01
Matrix	Correction	ZAF



Element	Wt%	At%
OK	03.67	06.97
CuL	23.93	11.45
AlK	72.40	81.58
Matrix	Correction	ZAF

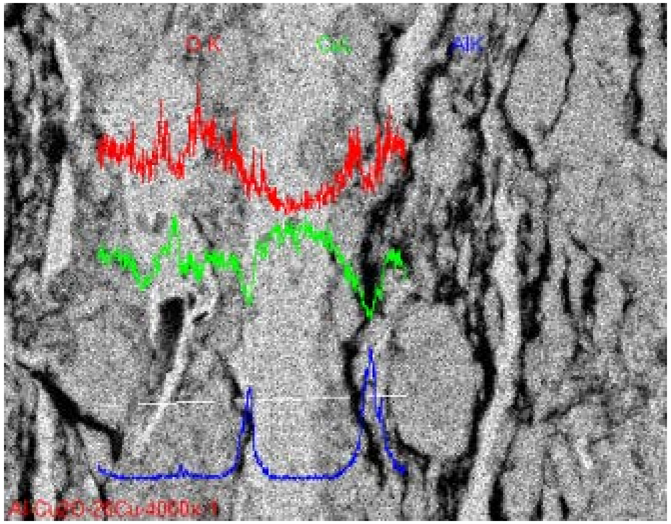
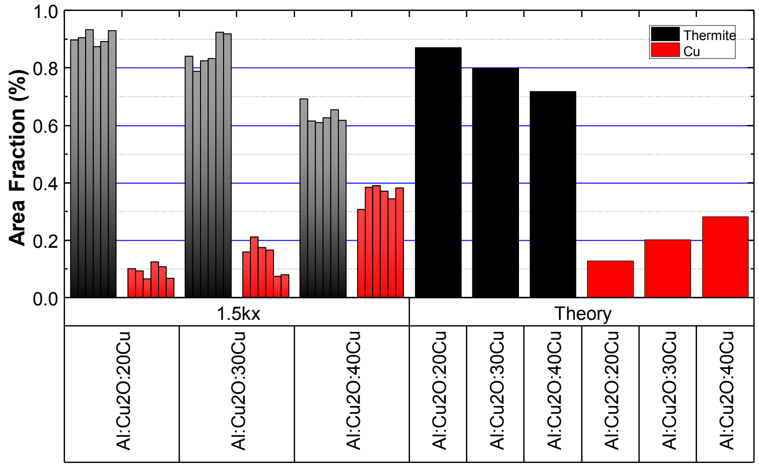
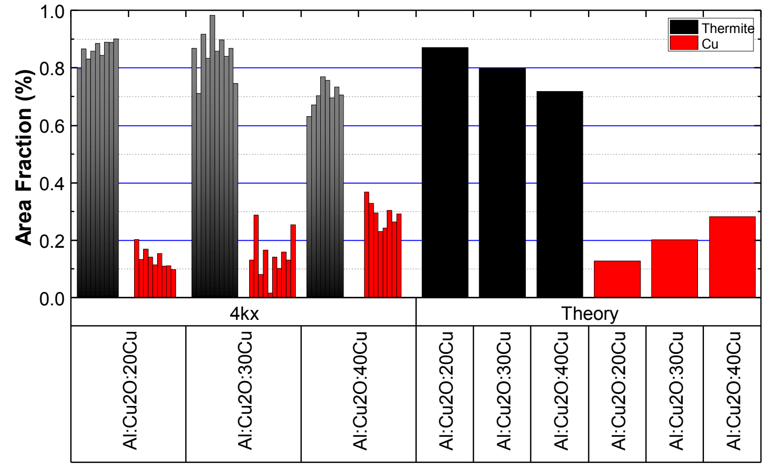


Image Analysis





- Clear non-uniformity in the resulting microstructure based on area fraction in image analysis.
- Depends on the area observed (magnification)